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Electronic Warfare & Radar Division
Systems Sciences Laboratory

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ABSTRACT

The dense wavelength-division multiplexing (DWDM) technique adds versatility, flexibility and performance to microwave photonic signal processing in Electronic Warfare (EW), high signal-to-noise ratio (SNR) communications links, optical fibre sensor networking and optical beamforming of phased-array antennas. The utilisation of DWDM requires multiple-wavelength laser devices. Continuous-wave (CW) multiple-wavelength erbium-doped fibre ring lasers (EDFRLs) have been suggested as an alternative to multiple laser diodes. However, multiple-wavelength lasing in EDFRLs is difficult to achieve due to homogeneous line broadening (HLB).

In this report, a new CW multiple-wavelength EDFRL design is proposed. Dynamic wavelength-dependent cavity loss is utilised to overcome the effects of HLB. Rate equations are modelled to verify the principle of operation of the CW multiple-wavelength EDFRL. Multiple-wavelength operation controlled by dynamic wavelength-dependent cavity loss is shown to be possible. The multiple-wavelength lasing is predicted to be highly sensitive to any change in the cavity loss, which indicates a requirement for an electronic control circuit to maintain a stable multiple-wavelength lasing operation.

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Multiple-Wavelength Erbium-Doped Fibre Ring Lasers Part I - Modelling and Simulations

Executive Summary

The application of the dense wavelength-division multiplexing (DWDM) technique offers versatility and flexibility over single-wavelength concepts. DWDM requires multiple-wavelength laser devices. Continuous-wave (CW) multiple-wavelength erbium-doped fibre ring lasers (EDFRLs) have been suggested as an alternative to multiple laser diodes. These EDFRLs have potential applications in microwave photonic signal processing in Electronic Warfare (EW), high signal-to-noise ratio communications links, fibre sensors, antenna remoting, optical beamforming for phased-array antenna, and wireless picocell communications, which are of interest to the Australian Defence Force (ADF).

Multiple-wavelength lasing in EDFRLs is difficult to achieve due to homogeneous line broadening (HLB). The focus of this report is on the proposal of a new CW multiple-wavelength EDFRL design, which utilises wavelength-dependent cavity loss to overcome the effects of HLB.

In this report, multiple-wavelength operation controlled by dynamic wavelength-dependent cavity loss in the proposed EDFRL is theoretically demonstrated to be possible by a rate-equation model. Multiple-wavelength lasing is predicted to be highly sensitive to any change in the cavity loss. This indicates a requirement for an electronic control circuit to maintain a stable multiple-wavelength lasing operation. The multiple-variable control solution to maintain constant optical power per wavelength will have practical applications in recirculating-loop photonic radio frequency memory (PRFM) and channel management in all-optical networking.

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Linh Nguyen received the BSc in 1992 and BE (EEE) in 1993 from the University of Adelaide, and PhD in 1997 from the Photonics Research Laboratory, Australian Photonics Cooperative Research Centre, Department of Electrical & Electronic Engineering, University of Melbourne.

He has held positions at the Photonics Research Laboratory, Vicom Australia Pty. Limited and Acterna Asia-Pacific Pty. Limited. He has also completed a Master of Marketing at the Melbourne Business School. He currently holds a Research Scientist position in the Electronic Warfare & Radar Division, DSTO Edinburgh, where his research interests are in the field of microwave photonic signal processing and its applications to Electronic Warfare. He is the Task Manager for Photonic Systems Technology in the Electronic Warfare & Radar Division.

Contents

1. Introduction

Dense wavelength-division multiplexing (DWDM) laser sources are applicable in Electronic Warfare (EW) microwave photonic receivers [1], photonic radar pulse compressor and decompressor [2,3], high signal-to-noise ratio communications links, fibre sensors, antenna remoting, beamforming for phased-array antenna and wireless picocell communications.

1.1 Research Relevance

Continuous-wave (CW) multiple-wavelength erbium-doped fibre ring lasers (EDFRLs) are potential DWDM transmitters [4-6] for defence applications. Other technologies providing multiple-wavelength emission include Raman fibre lasers [7,8], erbium-doped waveguide grating based devices [9,10], semiconductor optical amplifier based lasers [11], and integrated laser diodes on a single substrate [2]. The main reason for choosing to investigate the EDFRL technology for defence applications is its simplicity.

An enabling research and development project was funded by the Optoelectronic Hub to investigate EDFRLs for defence applications. If successful, EDFRLs will become part of the Long Range Research program supporting the photonic systems technology research.

1.2 Multiple-Wavelength Emission

EDFRLs are commercially available [13], but only single-wavelength operation is available. Multiple-wavelength emission is difficult to obtain due to homogeneous line broadening (HLB) [4]. HLB is closely related to the wavelength dependence of the emission (gain) and absorption (loss) cross-sections in erbium-doped fibres [14,15]. A number of methods have been investigated for EDFRLs to overcome HLB to achieve multiple-wavelength emission:

1. Reduction of HLB in erbium-doped fibres by cooling in liquid nitrogen to 77 K [16,17].
2. Eliminating the limits associated with HLB by utilising an erbium-doped gain medium for each wavelength multiplexed together through arrayed-waveguide grating multiplexers (AWGMs) [18,19].

However, the most promising technique to overcome HLB is by frequency translation with an acousto-optic frequency shifter (AOFS) [4-6]. Multiple-wavelength emission is achievable at room temperature with commercial-off-the-shelf (COTS) components. There is no specific requirement of the multiple-wavelength emission on the acousto-optic frequency translation, because it does not need the ring cavity to be mode locked [4,5]. In fact, the AOFS acts as a variable optical attenuator (VOA) equalising gain and cavity loss at each lasing wavelength [6].

1.3 Report Focus

A new CW EDFRL is proposed using in-line VOAs to control HLB, and thereby to excite multiple-wavelength emission. The use of the in-line VOAs is equivalent to having a dynamic wavelength-dependent cavity loss. In order to theoretically verify the principle of operation of the proposed EDFRL, rate equations are programmed to investigate how the proposed EDFRL would function. This forms the main focus of this research report.

Simulated results from the model show that multiple-wavelength emission is possible by dynamically controlling the wavelength-dependent cavity loss. However, the multiple-wavelength emission is highly sensitive to the wavelength-dependent cavity loss. This indicates that an active electronic control circuit would be required to maintain constant optical power per wavelength. Such a multiple-variable control solution will have direct application in recirculating-loop photonic radio frequency memory (PRFM) [3], which is another ongoing research effort within the Electronic Warfare & Radar Division.

This research report summarises the outcomes from the modelling and simulation of the proposed EDFRL. It is structured as:

- *Ring Laser Design* section details the proposed CW multiple-wavelength EDFRL design.
- *Ring Laser Rate-Equation Model* section outlines the rate equations to simulate the proposed EDFRL.
- *Multiple-Wavelength Simulation* summarises the results from the simulation of the EDFRL to verify the feasibility of multiple-wavelength emission. It also demonstrates the need for an active electronic control loop to maintain constant optical power per wavelength.
- *Conclusions* summarise the findings of this report.
- *Recommendations* detail future research directions.

2. Ring Laser Design

A continuous-wave (CW) erbium-doped fibre ring laser (EDFRL) consists of an erbium-doped fibre amplifier (EDFA), a fibre ring cavity, an optical coupler and a multiple-wavelength bandpass filter [4-6,16-19]. Optical isolators and polarisation controllers (PCs) can also be used to optimise the laser performance. The multiple-wavelength bandpass filter selects the desired lasing wavelengths. Each of the lasing modes contains simultaneous fine lines representing the ring cavity modes, whose spacing is dependent on the cavity length. Homogeneous line broadening (HLB) in erbium-doped fibres has to be overcome to excite multiple-wavelength emission [4-6].

Taking into account the above design considerations, a new CW multiple-wavelength EDFRL is proposed and illustrated in Figure 1. The in-line variable optical attenuators (VOAs) form a dynamic wavelength-dependent cavity loss to control HLB. This dynamic control mechanism for multiple-wavelength emission was proposed independent of the conclusions of Reference 5, which suggested that the spectrum of multiple-wavelength EDFRLs could be reshaped with in-line VOAs.

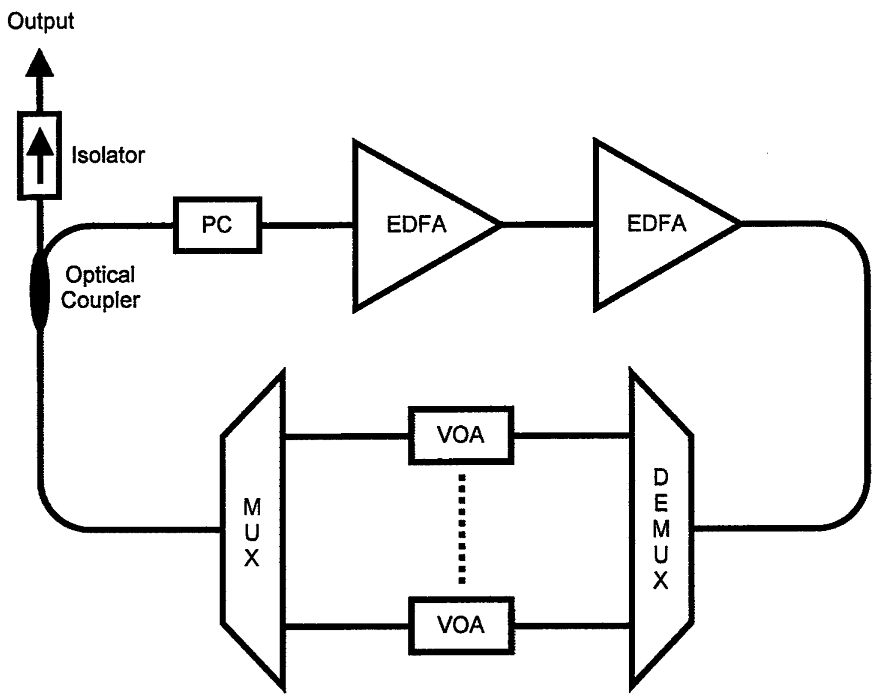


Figure 1: Design of a continuous-wave multiple-wavelength erbium-doped fibre ring laser.

Other EDFRL design issues were considered:

1. Two EDFAs may be required to overcome high insertion losses of various photonic components in the ring cavity. In addition, two EDFAs would output high optical power to saturate themselves and thereby help to flatten lasing spectrum [14].

2. The multiple-wavelength bandpass filter is made up of a combination of optical demultiplexer (DEMUX) and multiplexer (MUX). These MUX and DEMUX devices must be a band-limited filter to ensure that lasing occurs only at specific wavelengths [4-6]. The VOAs are located between the DEMUX and MUX where the individual wavelength propagates separately, and thereby can be adjusted to compensate for the effects of HLB.

3. The optical coupler is located after the DEMUX-MUX filter to improve the optical signal-to-noise ratio [6]. The DEMUX-MUX filter reduces the amplified spontaneous emission (ASE) from the EDFAs prior to the output.

4. Each lasing wavelength may require a separate PC, which could be positioned between each VOA and the MUX. Polarisation-maintaining components can be used to eliminate problems associated with polarisation in the ring cavity, which are expensive.

5. The EDFAs have built-in input and output isolators forming part of the ring cavity, so only one isolator is required at the output port of the optical coupler to minimise external back-reflection.

There are possibilities of weak sub-cavities forming within the ring cavity due to back-reflections between various components. Since the CW emission is not mode-locked to any cavity mode, then the formation of weak sub-cavities would not be so critical. However, using components having low back-reflection would minimise the opportunity for these weak sub-cavities to form and help to promote stable lasing emission.

3. Ring Laser Rate-Equation Model

This section outlines a numerical model based on rate equations to simulate the proposed continuous wave (CW) multiple-wavelength erbium-doped fibre ring laser (EDFRL), as shown in Figure 1. The rate-equation model is easy to program to theoretically verify the principle of operation of the proposed EDFRL.

Rate-equations suitable for simulating EDFRLs model the erbium-doped fibres in alternative scenarios:

1. In the first version of the EDFRL rate-equation model, the emission and absorption cross-sections of erbium-doped fibres are spectrally and spatially resolved [20], which would allow the co-propagating pump, signal and amplified spontaneous emission powers to be accurately modelled. This enables nonlinear effects such as spectral- and spatial-hole burning to be simulated.

2. In the second version of the model, the erbium-doped fibres are modelled as lumped elements in which both emission and absorption cross-sections are averaged out [21,22]. This approach is accurate only if the EDFRLs are such that the transit time of the resonator is shorter than the pulses that occur during relaxation oscillations [21]. The advantage is that it is a lot simpler to implement than the first version, but it does not simulate nonlinear effects.

The lumped-element EDFRL rate-equation model [21,22] is judged to be sufficient in providing the theoretical proof of the principle of operation of the proposed CW multiple-wavelength EDFRL depicted in Figure 1. Reference 21 described a set of dual-wavelength model, which must be generalised to M wavelengths to model the proposed CW multiple-wavelength EDFRL. The rate equations for the EDFRLs can be characterised by the standard erbium three atomic energy levels consisting of the ground level $^4I_{15/2}$, metastable level $^4I_{13/2}$ and intermediate or pump level $^4I_{11/2}$ [14,21,22]. These energy levels are denoted as 1, 2 and 3, respectively. The complete set of rate equations describing a multiple-wavelength EDFRL is:

$$\frac{dN_3}{dt} = W_p N_1 - \frac{N_3}{\tau_{32}} \tag{1}$$

$$\frac{dN_2}{dt} = \frac{N_3}{\tau_{32}} - \frac{N_2}{\tau_{21}} - \sum_{i=1}^{M} \frac{\eta_s}{A}\left(\sigma_e[\lambda_i]N_2 - \sigma_a[\lambda_i]N_1\right)\frac{S[\lambda_i]}{\tau_c} \tag{2}$$

$$N_1 = N_c - N_2 - N_3 \tag{3}$$

$$\frac{dS[\lambda_i]}{dt} = \frac{\eta_s I_a}{\tau_c}\left(1 + S[\lambda_i]\right)\sigma_e[\lambda_i]N_2 - \frac{\eta_s I_a}{\tau_c} S[\lambda_i]\sigma_a[\lambda_i]N_1 - \frac{\delta_c[\lambda_i]}{\tau_c} S[\lambda_i] \tag{4}$$

Equation 1 describes the rate of change in population density of the intermediate level, which is made up of population density pumped up from the ground level and that decaying to the metastable level. Equation 2 is the rate of change in population density of the metastable level from which spontaneous and multiple-wavelength stimulated emissions occur. Equation 3 equates the total population density to the erbium dopant concentration. Finally, Equation 4 represents the rate of change in photon number at each lasing wavelength propagating in the ring cavity through stimulated emission and that being attenuated due to the absorption cross-section and total cavity loss.

The photon number at each lasing wavelength is modelled by spectrally resolving both emission and absorption cross-sections. The photon numbers at all lasing wavelengths in Equation 4 are coupled together through the population density rate equation of the metastable level in Equation 2. Therefore, the multiple-wavelength dynamics describing the interaction between lasing photon number is modelled [20-22]. Table 1 lists all symbols, definitions and parameters for the EDFRL rate-equation model described by Equations 1-4 [14,20-22].

Symbol	Definition	Value	Reference
N_1	Population density of the ground level	Variable	[14,21]
N_2	Population density of the metastable level	Variable	[14,21]
N_3	Population density of the intermediate level	Variable	[14,21]
N_c	Erbium dopant concentration	3.8×10^{24} m^{-3}	[21]
$S[\lambda_i]$	Photon number at lasing wavelength λ_i where $1 \le i \le M$	Variable	
$\delta_c[\lambda_i]$	Cavity loss factor at lasing wavelength λ_i	Variable	[21,22]
M	Number of lasing wavelengths	49	
$\sigma_e[\lambda_i]$	Emission cross-section at lasing wavelength λ_i	Variable	[14]
$\sigma_a[\lambda_i]$	Absorption cross-section at lasing wavelength λ_i	Variable	[14]
l_a	Active erbium-doped fibre length	6 m	[21]
l_c	Ring cavity length	10 m	[21]
τ_c	Ring cavity transit time as calculated from the total length using a refractive index of 1.5	50 nsec	[21]
τ_{32}	Decay lifetime from intermediate level to metastable level	7 μsec	[14]
τ_{21}	Decay lifetime from metastable level to ground level	10 msec	[14]
A	Effective fibre core area	5×10^{-12} m^2	[14]
W_p	Pump probability, which can be evaluated from the total pump power as in Reference 14	10000	
η_s	Signal power confinement factor in fibre core	0.5	
ΔT	Numerical integration time-step	5 nsec	

Table 1: Symbols and parameters for EDFRL rate-equation model [14,20-22].

Examples of emission and absorption cross-sections and their wavelength dependence for a typical erbium-doped fibre can be extracted from Reference 14. This is replotted in Figure 2. Samples from 1527-1566 nm would be used in the simulation of the proposed CW multiple-wavelength EDFRL, i.e. $M = 49$ with 0.8 nm spacing, to investigate the feasibility of multiple-wavelength emission.

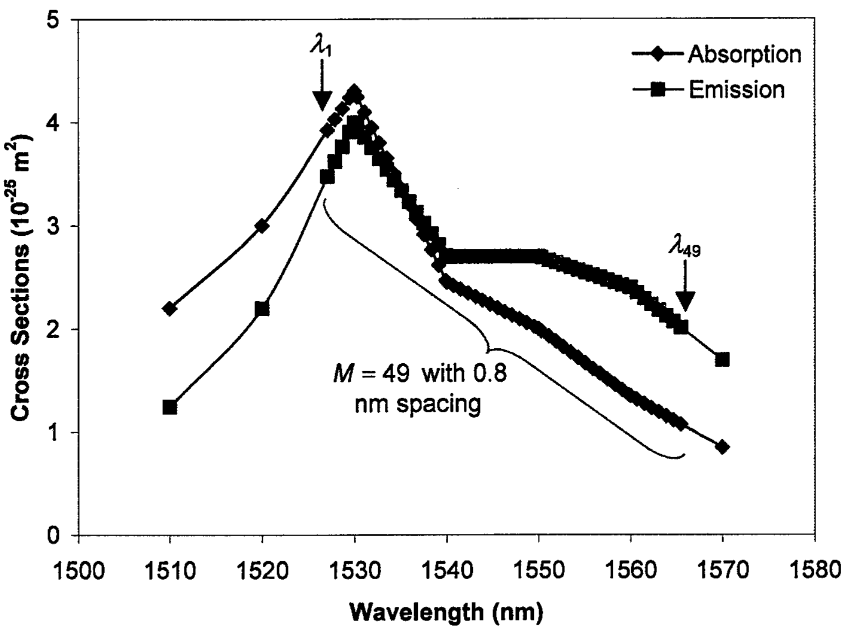


Figure 2: Emission and absorption cross-sections of a typical erbium-doped fibre as extracted from Reference 14.

The cavity loss factor at lasing wavelength λ_i is defined as [21-22]:

$$\delta_c[\lambda_i] = -\ln\left(\sum Losses\ at\ \lambda_i\right) \tag{5}$$

For example, if the total cavity loss at λ_i is 10 dB, then $\delta_c[\lambda_i] = 2.30$. Similarly, $\delta_c[\lambda_i] = 6.91$ represents a total cavity loss of 30 dB. The multiple-wavelength characteristics of the EDFRL are represented by the emission and absorption cross-sections together with the cavity loss factor in Equation 5.

It is worth noting that the rate equations, Equations 1-4, do not model a propagating optical field. Therefore, optical phase information cannot be evaluated and so linewidth is not modelled. Modifications to Equations 1-4 are required if linewidth is to be investigated.

4. Multiple-Wavelength Ring Laser Simulation

Equations 1-4 representing the proposed continuous-wave (CW) multiple-wavelength erbium-doped fibre ring laser (EDFRL), Figure 1, can be solved numerically by using a 4th-order Runge-Kutta integration process [23]. Equation 3 is substituted into Equations 1, 2 and 4 to reduce the number of variables to the number of coupled differential equations. The following initial conditions are also used to solve the coupled rate equations.

$$\begin{aligned} N_1 &= N_C \\ N_2 &= 0.0 \\ N_3 &= 0.0 \\ S[\lambda_i] &= 0.0 \end{aligned} \tag{6}$$

4.1 Single-Wavelength Dynamics

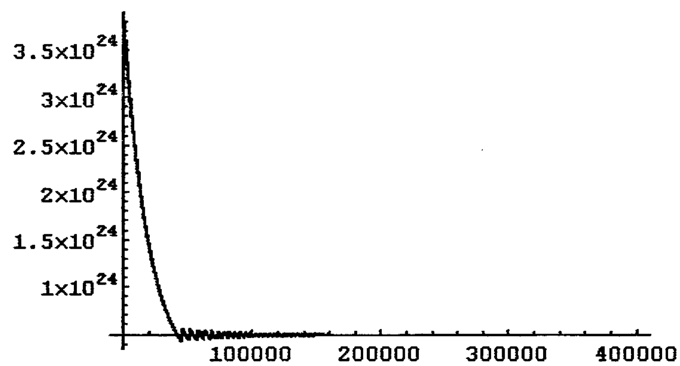
The rate-equation model, Equations 1-4, can simulate single-wavelength operation by using the following cavity loss factor:

$$\delta_C[\lambda_i] = \begin{cases} 2.30 & \text{if } \lambda_i \text{ is lasing} \\ 6.91 & \text{not lasing} \end{cases} \tag{7}$$

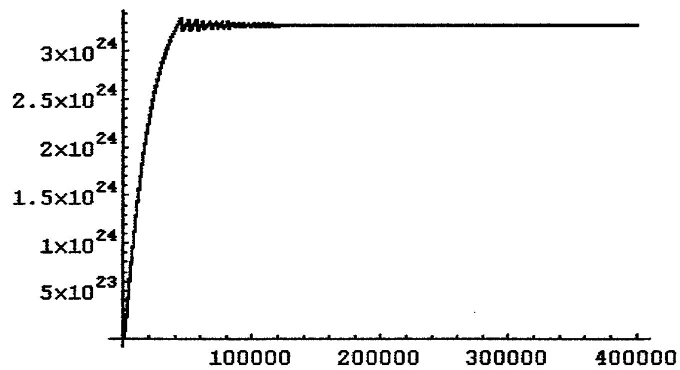
This is equivalent to a narrowband optical bandpass filter (e.g. fibre Bragg grating) having insertion loss contributing to total cavity loss of 10 dB and out-of-band rejection of 20 dB, which replaces the DEMUX-MUX filter shown in Figure 1.

The single-wavelength simulation is useful to demonstrate the transient dynamic behaviour of EDFRLs. Wavelength number 10 was allowed to lase in the model. The simulated transients of the population densities are as shown in Figure 3. It is worth noting that the majority of the excited states reside on the metastable level at steady state with model parameters as listed in Table 1. In comparison, the population density of the intermediate level is relatively small due to a faster decay time to the metastable level.

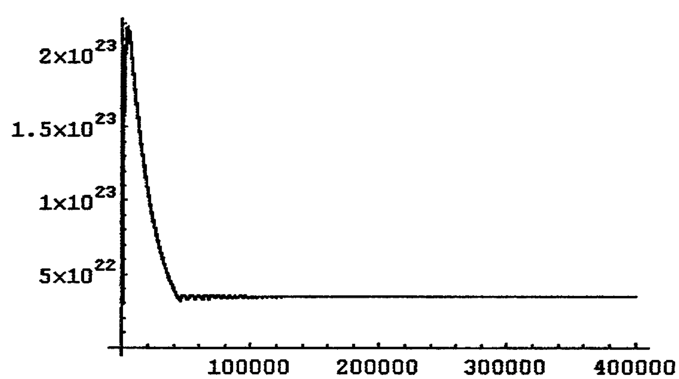
The simulated transient behaviour of photon number at wavelength number 10 is illustrated in Figure 4. The pulses resulted from the relaxation oscillation of the EDFRL are high in peak power as compared to the steady-state value. This is consistent with reported results in Reference 21, in which a nonlinear optical loop mirror was utilised to suppress such high-power relaxation oscillation to optimise tuning speed of a single-wavelength tunable EDFRL [21].



(a) Population density of the ground level, N_1.



(b) Population density of the metastable level, N_2.



(c) Population density of the intermediate level, N_3.

Figure 3: Simulated transient behaviour of population densities of ground, metastable and intermediate levels. Total data points of 400000 represent a simulation time of 2 ms.

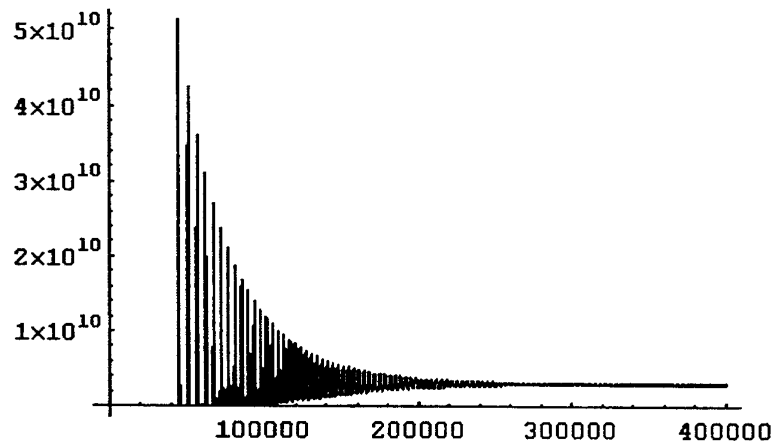


Figure 4: Simulated transient behaviour of photon number of lasing wavelength 10. Total data points of 400000 represent a simulation time of 2 ms.

Figure 5 shows a simulated spectrum of steady-state photon numbers from the model as the centre wavelength of the filter, Equation 7, is set to wavelength numbers 1, 10, 20, 30 and 40. This corresponds to simulation of wavelength tunability from a single-wavelength EDFRL.

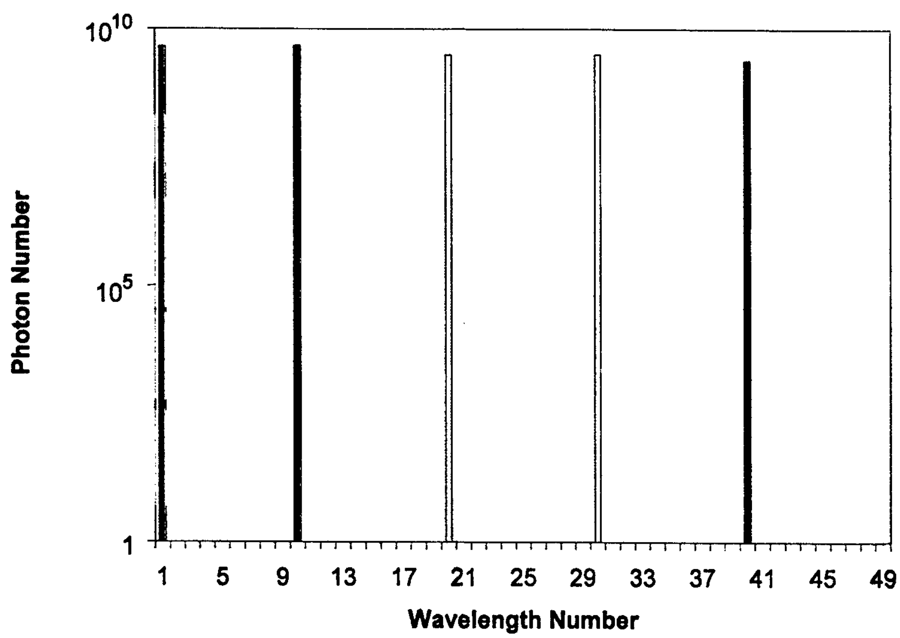


Figure 5: Simulated spectrum of steady-state photon numbers for wavelength numbers 1, 10, 20, 30 and 40 from single-wavelength simulations.

4.2 Multiple-Wavelength Dynamics

In semiconductor laser diodes, the material gain is wavelength dependent while the cavity losses are considered to be constant [15]. In comparison, both emission and absorption cross-sections in erbium-doped fibres are wavelength dependent as depicted in Figure 2, which is part of homogeneous line broadening (HLB). It is well known that HLB in erbium-doped fibres limits EDFRLs to lase at only one wavelength [14,20-22]. Simulations presented here would show how in-line variable optical attenuators (VOAs), forming a dynamic wavelength-dependent cavity loss, can overcome problems associated with HLB to excite multiple-wavelength emission in the proposed CW EDFRL described in Figure 1.

4.2.1 Unrestricted Free Spectral Range

In order to understand how in-line VOAs can be utilised to reshape the spectrum of the proposed EDFRL, various multiple-wavelength bandpass filters are simulated instead of the DEMUX-MUX filter depicted in Figure 1. The first filter considered is a Fabry-Perot etalon filter, whose bandpass response repeats at discrete wavelengths. Since Equations 1-4 models represent lasing only at discrete wavelengths, this case is also equivalent to when no filter is used. The etalon filter is represented by:

$$\delta_c[\lambda_i] = 2.30 \text{ for all } 1 \leq i \leq 49 \tag{8}$$

The simulated spectrum of the CW EDFRL using the above etalon filter is plotted in Figure 6, which shows that wavelength number 5 lases. This corresponds to the wavelength with the highest emission cross-section, which can be seen from Figure 2. Interestingly, the absorption cross-section is higher than emission at the same wavelength. However, $N_2 >> N_1$ at steady state and so $\sigma_e[\lambda_5]N_2 > N_1\sigma_a[\lambda_5]$. This is the population inversion condition. Figure 6 also demonstrates the observed characteristics of HLB. It is also interesting to note that the simulated side-mode suppression ratio (SMSR) in Figure 6 is high, which is consistent with commercial-off-the-shelf (COTS) single-wavelength EDFRLs [13].

It can be concluded from Figure 6 that multiple-wavelength emission cannot be promoted with Fabry-Perot etalon filters, which have unrestricted free spectral range. Its wavelength response repeats covering the complete spectrum of erbium-doped fibres. Therefore, lasing would occur only at the wavelength where the emission cross-section is highest. Arrayed-waveguide grating multiplexers are characterised to also exhibit unrestricted free spectral range, so they cannot be used as the multiple-wavelength bandpass filter in the proposed CW EDFRL. The unrestricted free spectral range must be limited by bandpass filtering to enable lasing to occur at desired wavelengths [20,21]. Such devices are referred to as band-limited periodic filters in this report.

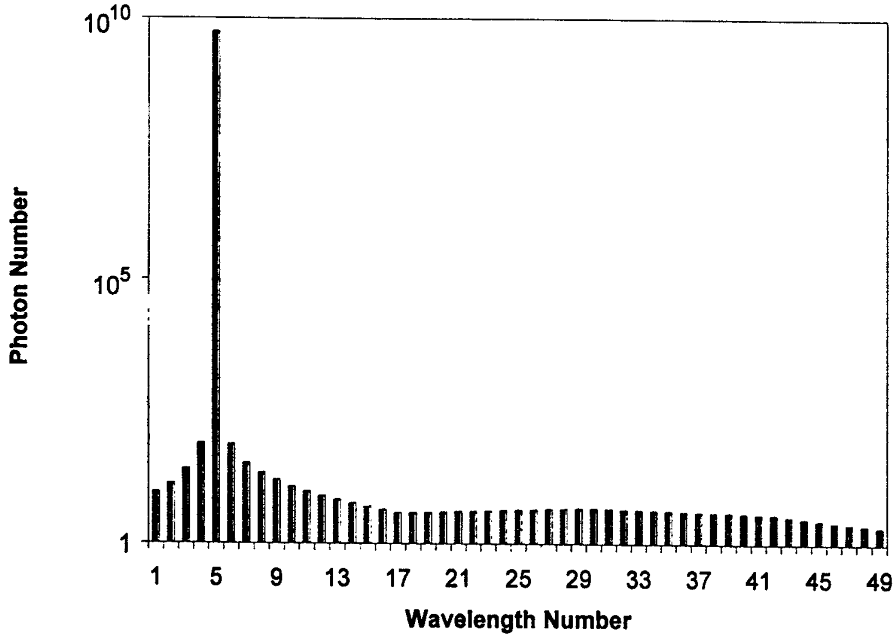


Figure 6: Simulated spectrum with a Fabry-Perot etalon filter.

4.2.2 Constant Emission and Absorption Cross-Sections

From Figure 2, the band including wavelength numbers 18-29 has constant emission cross-section of 2.7×10^{-25} m². This is the band where multiple-wavelength emission is most likely to occur. The following band-limited periodic filter can be used in the simulation:

$$\delta_c[\lambda_i] = \begin{cases} 2.30 & 18 \le i \le 29 \\ 6.91 & \text{elsewhere} \end{cases} \tag{9}$$

Simulation using a constant arbitrary absorption cross-section of 2.0×10^{-25} m² was performed. The simulated spectrum for this case is shown in Figure 7. The rate equations representing photon numbers for wavelength numbers 18-29 are now identical, and thereby have the same transient and steady state solutions. The simulated result presented here acts as a check on the integration process used to solve the EDFRL rate-equation model.

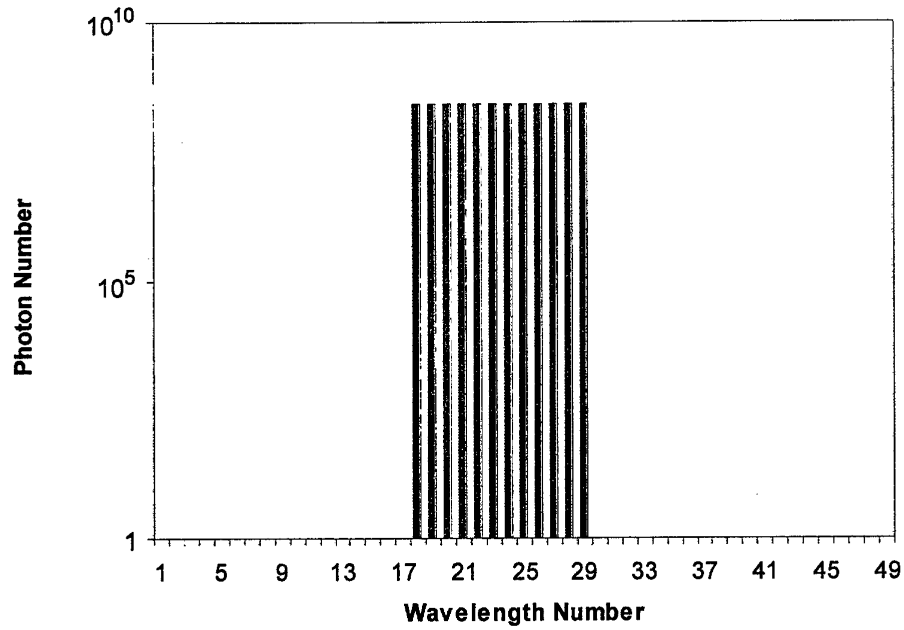


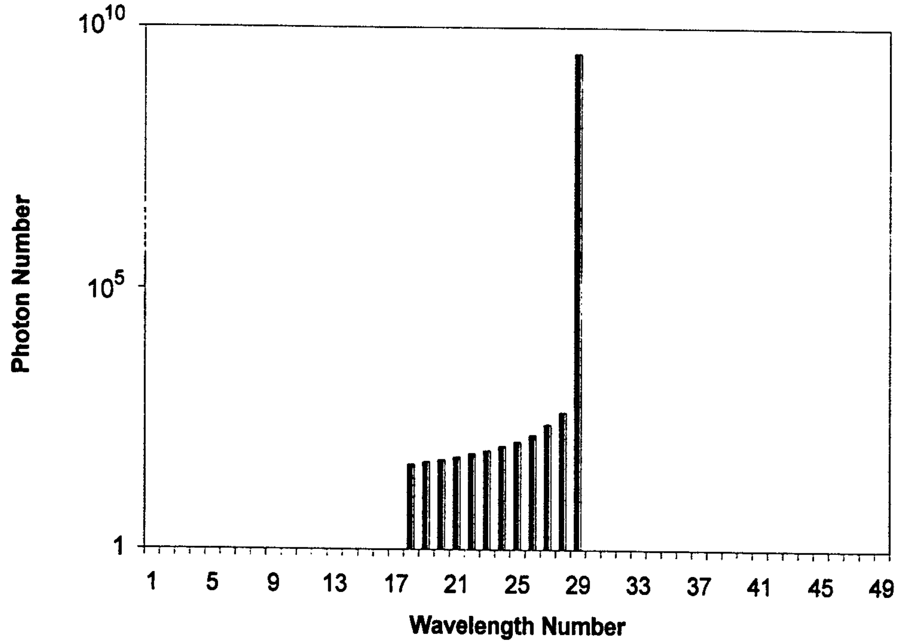
Figure 7: Simulated spectrum with constant emission and absorption cross-sections.

4.2.3 Natural Emission and Absorption Cross-Sections

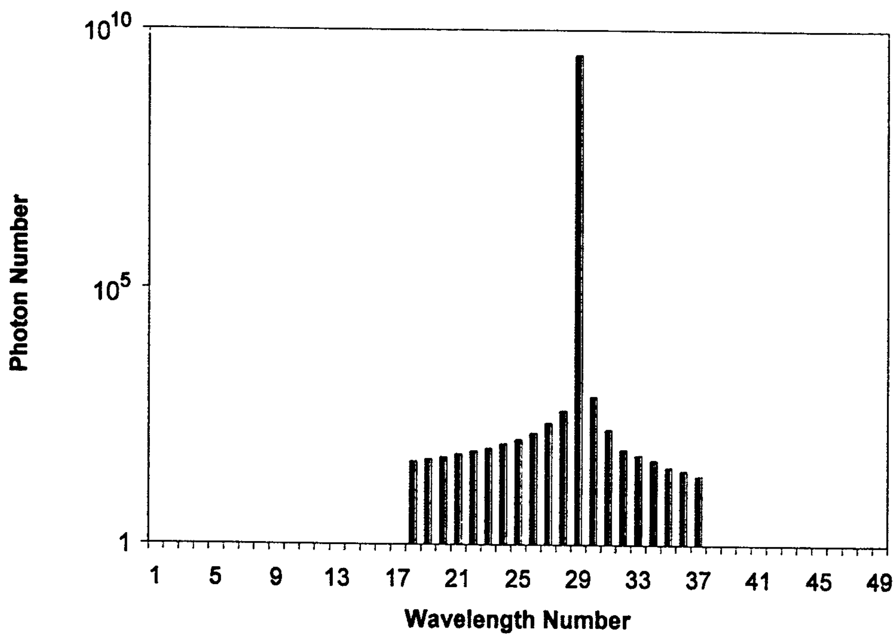
When natural emission and absorption cross-sections from Figure 2 are used together with the band-limited periodic filter in Equation 9, the simulated spectrum obtained is plotted in Figure 8(a). A band-limited periodic filter covering wavelength numbers 18-37 was also considered:

$$\delta_c[\lambda_i] = \begin{cases} 2.30 & 18 \leq i \leq 37 \\ 6.91 & \text{elsewhere} \end{cases} \tag{10}$$

The simulated spectrum obtained with Equation 10 is plotted in Figure 8(b). Both filters represented by Equations 9 and 10 promote single-wavelength lasing at wavelength number 29, where the emission cross-section is highest combining with the lowest absorption cross-section. It is this combination of highest emission cross-section and lowest absorption cross-section that demonstrates the observed characteristics of HLB limiting lasing to a single-wavelength in Figure 8. Variation in the emission and absorption cross-sections can lead to lasing at a different wavelength, where population inversion occurs first.



(a) Filter as described by Equation 9



(b) Filter as described by Equation 10

Figure 8: Simulated spectrum using natural emission and absorption cross-sections as shown in Figure 2 together with band-limited periodic filters in Equations 9 and 10.

The emission and absorption cross-sections shown in Figure 2 belong to a standard erbium-doped fibre amplifier (EDFA) without gain flattening. It is believed that gain-flattened EDFAs [24] would not promote perfect multiple-wavelength emission due to residual gain variation. In commercial gain-flattened EDFAs, the residual gain variation typically ranges from ~0.5 to 1 dB, which would be accumulated in the ring resonator through multiple recirculations creating an uneven spectrum.

4.2.4 Dynamic Wavelength-Dependent Cavity Loss

The solution to obtain multiple-wavelength emission by using in-line VOAs, shown in Figure 1, can be derived from rate equations, Equations 1-4. Recalling Equation 4, the following holds at steady state:

$$\frac{\eta_s I_a}{\tau_c}\left(1+S[\lambda_i]\right)\sigma_e[\lambda_i]N_2-\frac{\eta_s I_a}{\tau_c}S[\lambda_i]\sigma_a[\lambda_i]N_1-\frac{\delta_c[\lambda_i]}{\tau_c}S[\lambda_i]=0 \tag{11}$$

Rearranging Equation 11 above gives:

$$\frac{1+S[\lambda_i]}{S[\lambda_i]}=\frac{\eta_s I_a\sigma_a[\lambda_i]N_1+\delta_c[\lambda_i]}{\eta_s I_a\sigma_e[\lambda_i]N_2} \tag{12}$$

Multiple-wavelength emission occurs if $S[\lambda_i]=S[\lambda_{i+1}]$, which implies that:

$$\frac{1+S[\lambda_i]}{S[\lambda_i]}=\frac{1+S[\lambda_{i+1}]}{S[\lambda_{i+1}]} \tag{13}$$

$$\frac{\eta_s I_a\sigma_a[\lambda_i]N_1+\delta_c[\lambda_i]}{\eta_s I_a\sigma_e[\lambda_i]N_2}=\frac{\eta_s I_a\sigma_a[\lambda_{i+1}]N_1+\delta_c[\lambda_{i+1}]}{\eta_s I_a\sigma_e[\lambda_{i+1}]N_2} \tag{14}$$

Note that both population densities N_1 and N_2 are common for all wavelengths. Rearranging Equation 14 gives:

$$\delta_c[\lambda_{i+1}]=\eta_s I_a N_1\left\{\frac{\sigma_e[\lambda_{i+1}]}{\sigma_e[\lambda_i]}\sigma_a[\lambda_i]-\sigma_a[\lambda_{i+1}]\right\}+\frac{\sigma_e[\lambda_{i+1}]}{\sigma_e[\lambda_i]}\delta_c[\lambda_i] \tag{15}$$

Multiple-wavelength emission can be excited if the differences in emission and absorption cross-sections can be equalised wavelength-dependent cavity loss factors according to Equation 15. One technique to incorporate the wavelength-dependent cavity loss factors in EDFRLs is by using an acousto-optic frequency shifter (AOFS) [20-22]. In the proposed CW multiple-wavelength EDFFL, in-line VOAs are used as shown in Figure 1. The in-line VOAs can also function to balance unequal insertion losses of components in the ring cavity. These VOAs form a dynamic wavelength-dependent cavity loss in the proposed EDFRL.

If the emission cross-sections are the same in a particular band of wavelengths, i.e. $\sigma_e[\lambda_i] = \sigma_e[\lambda_{i+1}]$, then Equation 15 is reduced to:

$$\delta_c[\lambda_{i+1}] = \eta_s I_a N_1 \{\sigma_a[\lambda_i] - \sigma_a[\lambda_{i+1}]\} + \delta_c[\lambda_i] \quad (16)$$

From Figure 2, Equation 16 holds for wavelength number 18-29. Simulation, based on the filter described by Equation 9 and cavity loss factors adjusted according to Equation 16, was performed. The simulated multiple-wavelength emission result is shown in Figure 9. There is a variation of 4.3 dB in the photon numbers. The reason for this variation is unknown. It is suspected that such variation might be due to the imperfect rate-equation simulation of the gain saturation and clamping effects in erbium-doped fibres [14].

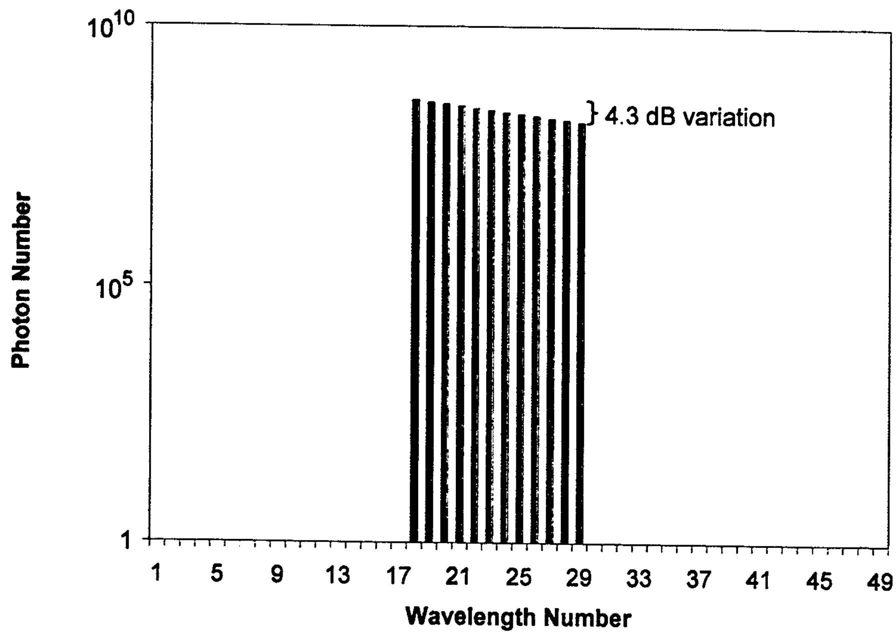


Figure 9: Simulated spectrum of multiple-wavelength emission based on Equation 16.

A similar simulation was performed for wavelength numbers 29-37. Equation 15 was used to evaluate cavity loss factors for multiple-wavelength emission together with a new filter:

$$\delta_c[\lambda_i] = \begin{cases} 2.30 & 29 \le i \le 37 \\ 6.91 & \text{elsewhere} \end{cases} \tag{17}$$

Figure 10 shows the simulated result. Again, multiple-wavelength emission is possible with a variation of 7.3 dB in photon numbers across the band.

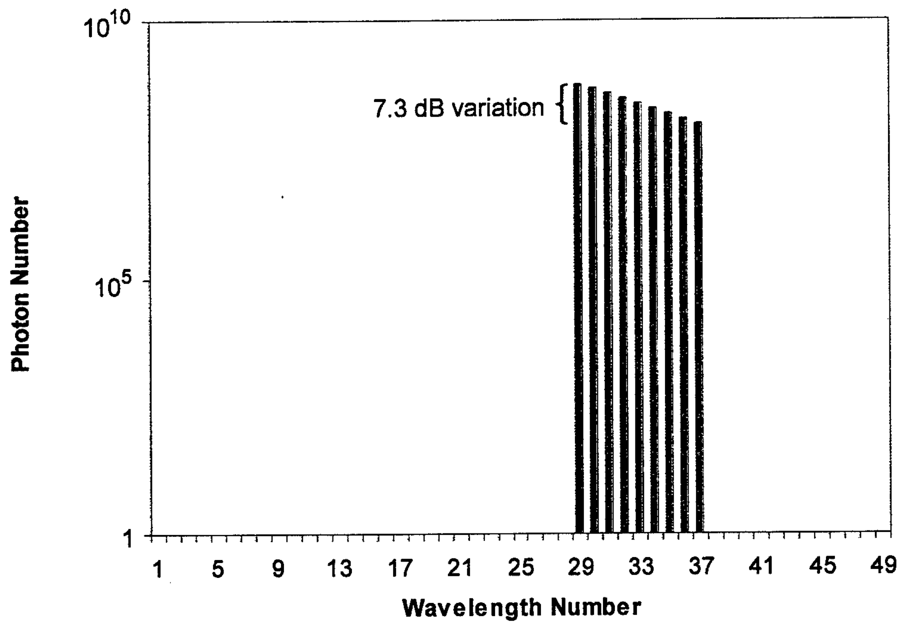


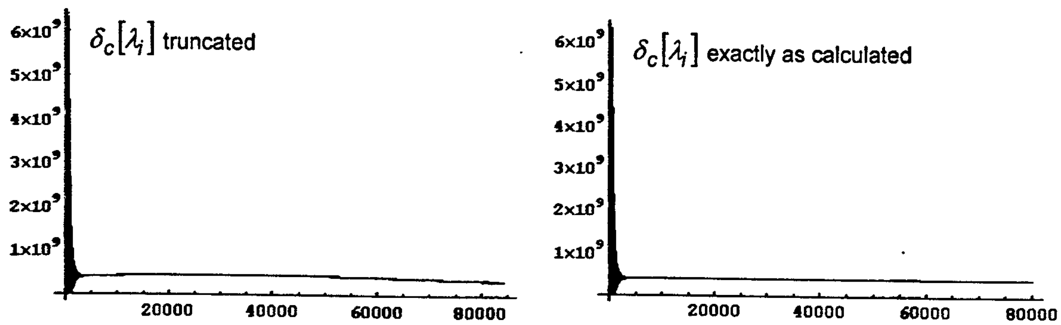
Figure 10: Simulated spectrum of multiple-wavelength emission based on Equation 15.

4.2.5 Sensitivity of Multiple-Wavelength Emission on Cavity Loss

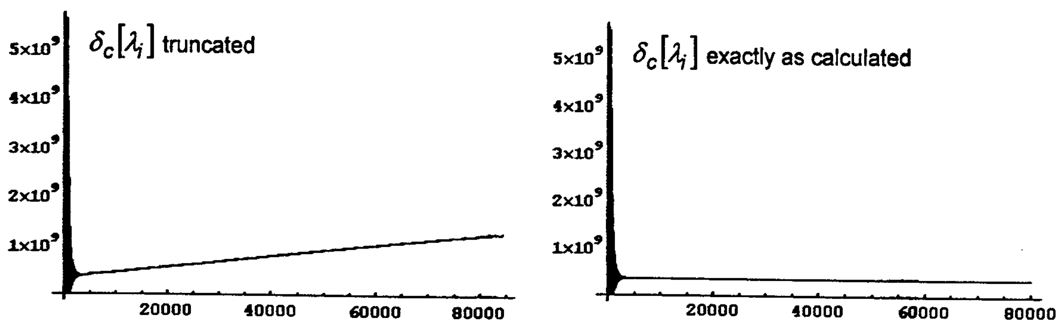
Figures 9 and 10 show that multiple-wavelength emission can be excited through the use of dynamic wavelength-dependent cavity loss, which is made up of in-line VOAs. In both cases, the required cavity loss factors are exactly as calculated and updated regularly in the model using Equations 16 and 15, respectively.

Taking the simulated result presented in Figure 9, multiple-wavelength emission was no longer possible when the required cavity loss factors were truncated to 5 decimal places and fixed during the simulation. On closer inspection of the transient behaviour of the photon numbers, slow transient dynamics are observed. These slow dynamics are represented in Figure 11, in comparison with perfect transients representing result

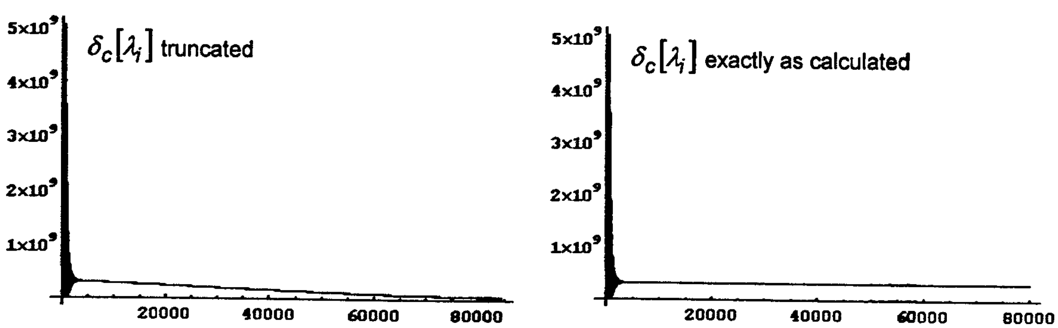
Figure 9. The truncation process has upset the equalisation dynamic to achieve multiple-wavelength emission provided by Equations 15. Rounding up the cavity loss factor suppresses lasing in the long term. Rounding down on the other hand gives that wavelength additional gain to eventually dominate. Multiple-wavelength emission is no longer possible.



(a) Wavelength number 18.



(b) Wavelength number 19.



(c) Wavelength number 20.

Figure 11: Slow dynamics of photon numbers due to the truncation of the calculated cavity loss factors for multiple-wavelength emission. The transients with steady states are from the simulations shown earlier in Figure 9 with cavity loss factors exactly as calculated in the model. Total data points of 80000 represent a simulation time of 40 ms.

In order to stabilise the VOAs in the proposed EDFRL, an active electronic control circuit is required as shown in Figure 12. This requires a high-speed multiple-variable control solution, because dynamic power equalisation must occur simultaneously at multiple wavelengths. Such degree of complexity is required since the EDFAs are now being operated in a ring resonator [24].

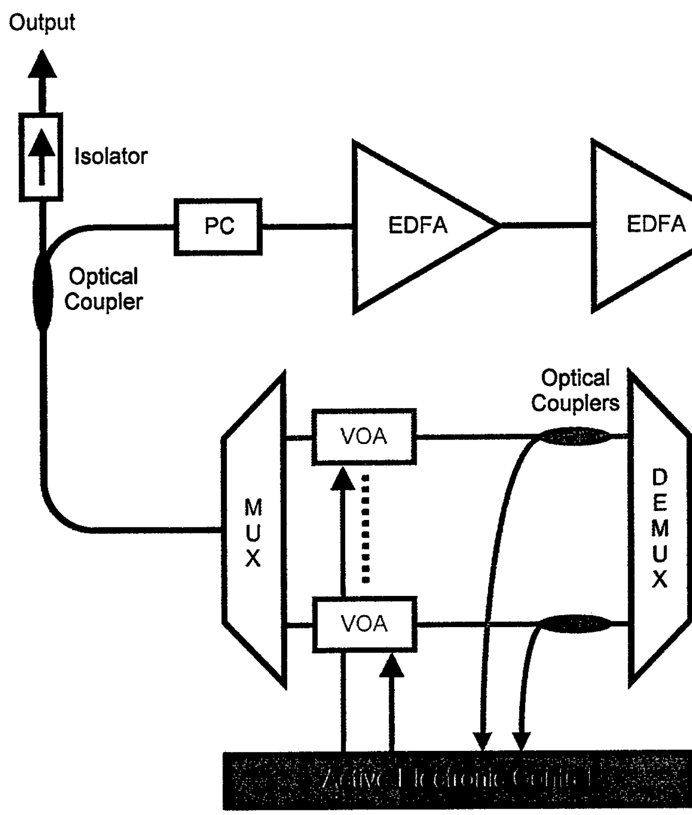


Figure 12: Proposed design of a continuous-wave erbium-doped fibre ring laser with dynamic balancing of power per wavelength.

The mechanics of high-speed dynamic balancing of power per wavelength is a critical research area with immediate application in recirculating-loop photonic radio frequency memory (PRFM) [3]. In telecommunications, it is applicable to channel management in all-optical networking. The recirculating-loop PRFM is similar in design to the proposed CW multiple-wavelength EDFRL [3]. Therefore, the same technique for balancing power per wavelength could be used. The active electronic control circuitry will need to function within a fraction of the radar pulsewidth in the recirculating-loop PRFM.

4.2.6 Linewidth

The rate-equation model described in this section does not predict linewidth of the proposed CW multiple-wavelength EDFRL. However, there is evidence in the literature that the linewidth of all CW EDFRL is intrinsically ~1 GHz. The linewidth of the multiple-wavelength EDFRL in Reference 20 and 21 was measured to be 1 GHz, while the specified linewidth of COTS single-wavelength EDFRLs is typically 1.3 GHz.

4.3 Conclusions

The theoretical proof of operation of the proposed CW multiple-wavelength EDFRL design, shown in Figure 1, has been demonstrated by using rate equations. Multiple-wavelength emission is feasible by using a dynamic wavelength-dependent cavity loss, which is made up of in-line VOAs. However, the multiple-wavelength emission is highly sensitive to the variation of the wavelength-dependent cavity loss. The proposed CW multiple-wavelength EDFRL needs to have an active electronic control circuit to maintain constant optical power per wavelength. The technique for balancing power per wavelength for the EDFRL also has an immediate application in recirculating-loop PRFM.

5. Summary

This report is the first part in a series summarising the research into continuous-wave (CW) multiple-wavelength erbium-doped fibre ring laser (EDFRL). A new design for a multiple-wavelength CW EDFRL was proposed in this report. The proposed EDFRL design uses dynamic wavelength-dependent cavity loss to overcome problems associated with homogeneous line broadening (HLB), and thereby excite multiple-wavelength emission. This technique was developed independent of the supportive conclusions in Reference 5.

The focus of this report is on modelling and simulation. A numerical rate-equation model suitable for CW multiple-wavelength EDFRL was programmed. The model was able to predict multiple-wavelength emission by utilising dynamic wavelength-dependent cavity loss, which is made up of in-line variable optical attenuators (VOAs). Simulation also indicates that the multiple-wavelength emission is highly sensitive to the changes in the wavelength-dependent cavity loss, leading to the requirement to incorporate an active electronic control circuitry into the design of the CW multiple-wavelength EDFRL. This control circuitry will also overcome nonlinear effects such as spatial-hole burning, which can suppress multiple-wavelength emission.

The technique for balancing power per wavelength to sustain multiple-wavelength emission highlighted above has an immediate application in recirculating-loop photonic radio frequency (RF) memory (PRFM) for Electronic Warfare applications.

6. Recommendation

The recommendation from this report is to verify experimentally the operation of proposed continuous-wave multiple-wavelength erbium-doped fibre ring laser.

7. Acknowledgement

The author would like to acknowledge the provision of enabling research and development (ER&D) financial support from the Optoelectronic Hub, Defence Science and Technology Organisation. The fund enabled the acquisition of photonic components for the experimental verification of the principle of operation of the proposed continuous-wave multiple-wavelength erbium-doped fibre ring laser.

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19. ABSTRACT
The dense wavelength-division multiplexing (DWDM) technique adds versatility, flexibility and performance to microwave photonic signal processing in Electronic Warfare (EW), high signal-to-noise ratio (SNR) communications links, optical fibre sensor networking and optical beamforming of phased-array antennas. The utilisation of DWDM requires multiple-wavelength laser devices. Continuous-wave (CW) multiple-wavelength erbium-doped fibre ring lasers (EDFRLs) have been suggested as an alternative to multiple laser diodes. However, multiple-wavelength lasing in EDFRLs is difficult to achieve due to homogeneous line broadening (HLB).

In this report, a new CW multiple-wavelength EDFRL design is proposed. Dynamic wavelength-dependent cavity loss is utilised to overcome the effects of HLB. Rate equations are modelled to verify the principle of operation of the CW multiple-wavelength EDFRL. Multiple-wavelength operation controlled by dynamic wavelength-dependent cavity loss is shown to be possible. The multiple-wavelength lasing is predicted to be highly sensitive to any change in the cavity loss, which indicates a requirement for an electronic control circuit to maintain a stable multiple-wavelength lasing operation.

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